Conference on Advanced Power Systems for Deep Space Exploration

Power Beaming for Deep Space and Permanently Shadowed Regions

Jonathan Grandidier[1], Malcolm Wright[1], Dimitri Krut[2], Bill Nesmith[1] and John Brophy[1]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

[2]Boeing Spectrolab Inc., Sylmar CA 91342

Jet Propulsion Laboratory
California Institute of Technology

Outline

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InGaAs laser power converter (LPC) device result

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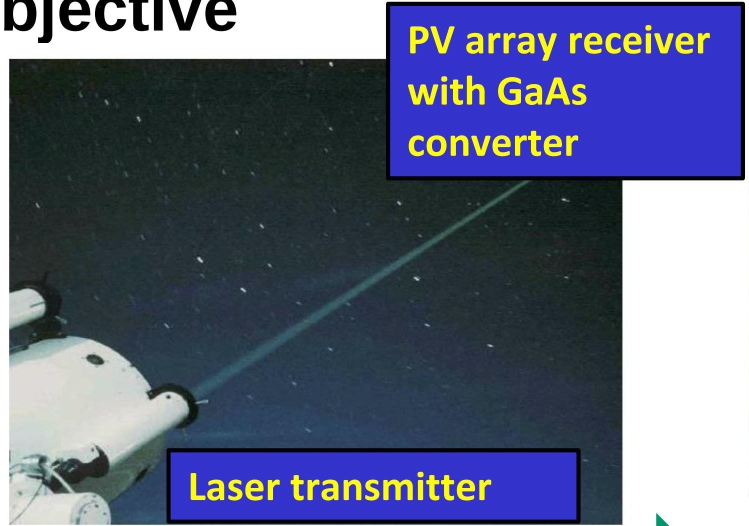
Examples of End to End Power Systems Utilizing Power Beaming

Objective



InGaAs Laser Power Converter.

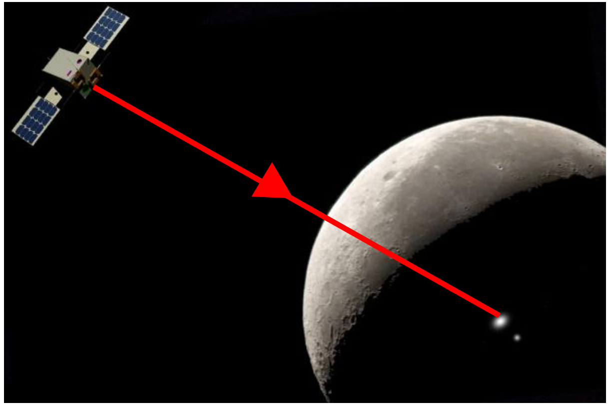
Electrical to Optical Conversion → Transmission → Optical to Electrical Conversion

The objective is to assess the technical feasibility of using an advanced laser power converter (LPC) to achieve high optical to electrical conversion efficiency.

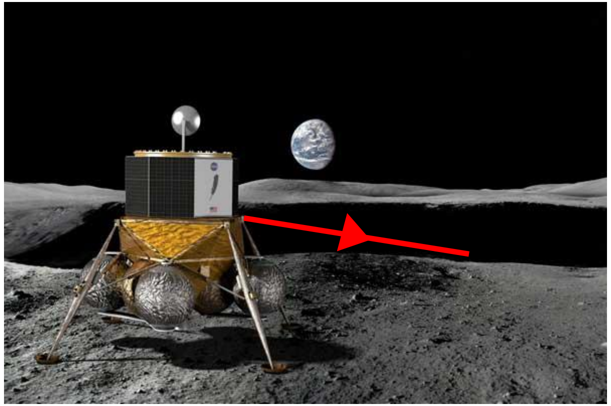
1) Short distance surface-to-surface power beaming (Short term)
   - Permanently shadowed regions (Moon's Shackleton crater), cavern regions
2) Longer distance orbit to surface beaming at the Moon/near the Sun (Mid term)
   - Powering landers and Rovers from orbiting spacecraft (Moon, Mars, Europa, Enceladus…)
3) Very high power beaming at distances very far from the Sun (Far term)
   - Transmitting power to outer planet spacecraft (beyond Jupiter)

Technology Description

J. Grandidier, M. W. Wright, D. Krut, B. J. Nesmith, and J. R. Brophy, "Power Beaming for Deep Space and Permanently Shadowed Regions," in The 2nd Optical Wireless and Fiber Power Transmission Conference (OWPT2020), Yokohama, Japan, 2020.



Orbiting solar-powered vehicle provides power to a lunar base during lunar night.



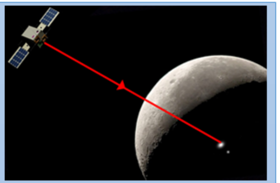
Power beaming to a rover in the permanently shadowed Shackleton crater. Artist's concept of Blue Origin's Blue Moon lunar lander. Credit: Blue Origin.

➢ Past Experience

- Power Beaming: NRL demonstrated transmission of 400 W of power, using large components, across 325 meters using a near infrared laser beam (October 2019).
- EADS ROVER power beaming demonstration. Transmission distance was between 30 meters and 200 meters. Power level was 4.3 W using a 532 nm laser (2004).

"Laser Power Beaming for Lunar Night and Permanently Shadowed Regions", J. Grandidier, P. Jaffe, W. T. Roberts, M. W. Wright, A. A. Fraeman, C. A. Raymond, A. Austin, P. Lubin, E. T. Sunada, J.-P. Jones, A. Barchowsky and J. D. Baker. White paper for the LEAG Decadal Survey (2020)

Concept:

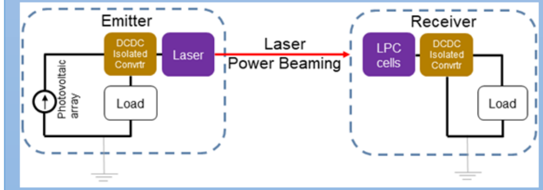


Laser Power Beaming[1] enables the transmission of power without wires.

The objective is:

- Charge a small robotic power system located in a permanently shadowed region (PSR) from a solar powered lander located at the rim of a crater.
- Provide power to a lunar base from an orbiter during the lunar night.

Terrestrial free-space power beaming demonstration NRL, May 2019



End-to-end power beaming system

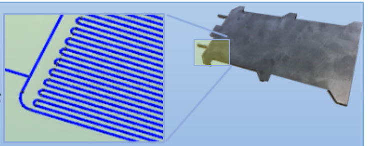
CabEx Concept

Laser and Optical Element[2]:

A CW fiber laser is used to beam a 1 kW optical laser beam at 1064 nm wavelength. The laser includes optical element for a receiver diameter beam at a 15 km target (rim to crater) or at a 65,000 km target (orbit to surface).

Thermal Management[3]:

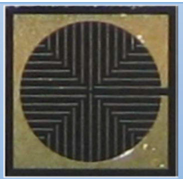
To generate a 1 kW optical laser beam, 3 kWe powers the 33% efficient fiber laser and 2 kW of heat needs to be rejected. This requires a 4 m^2 radiator for continuous operation.



Multi-functional radiator with embedded oscillating heat pipe technology

Laser Power Converter[4]:

The InGaAs laser power converter (LPC) array operates at a 65% goal for optical to electrical conversion efficiency. With a 1.1 eV bandgap (1130 nm), InGaAs is tuned for optimum conversion efficiency at 1064 nm.



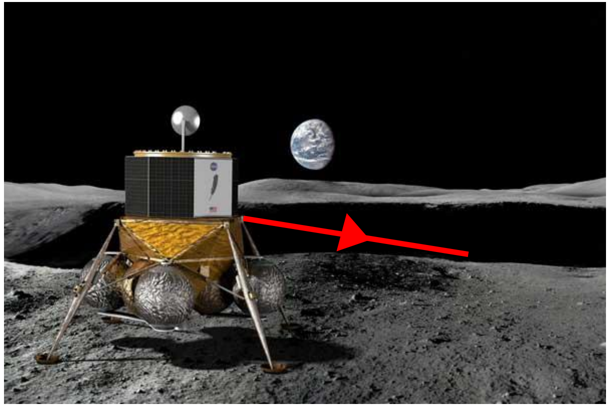
Power Electronics[5]:

GaN-based DC-DC converter modules for step up and step down conversion at 1kW+, 95% efficient from 100V-1.5kV. dc-dc power converters for lander and rover. APOGEE Semiconductor: Power controller IC development via NASA Tipping Point

1 = J. Grandidier/JPL, P. Jaffe/NRL, 2 = T. Roberts, M. Wright/JPL, 3 = E. Sunada/JPL, 4 = Photovoltaic Vendor, 5 = A. Barchowsky/JPL

NASA Relevance/Applications/Missions

Transmitter



1 kW laser
20 kg

2 m^2 double sided Thermal management
12 kg

20 cm aperture optical element
10 kg

3 kW solar array
14 kg

Power electronics
3 kg

Tracking element
8 kg

Receiver

John Elliott
"Notional Concept"

Battery 6.2 hours charge – 20 hours roving
36 kg

0.3 m diameter LPC array
0.15 kg

Power electronics
0.65 kg

Comparison Solar Photovoltaics / Power Beaming

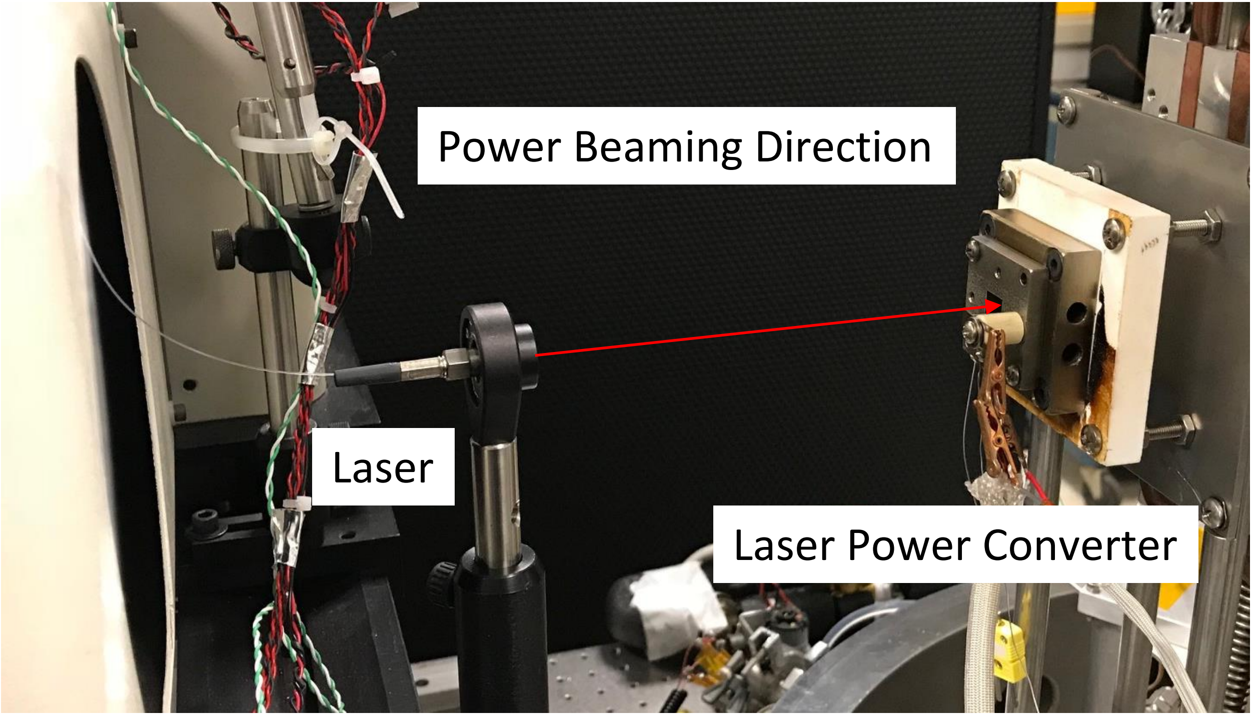
Mission	Power Generated Solar photovoltaics ($W\ m^{-2}$)	Generated Power Beaming (W)	Comparison vs Solar Photovoltaics
Permanently shadowed regions – e.g. Moon's Shackleton crater	N/A	650(1) or (2)	Mission Enabler
Continuous power throughout the lunar night	437 during day and not scalable	650(1) continuous and scalable	For Solar Photovoltaic, this would require a 3 m^2 solar array and a large amount (336 h) of Chemical Energy Storage. Power Beaming would eliminate chemical energy storage.
Shadowed cliff and cavern regions	N/A	650(2)	Mission Enabler

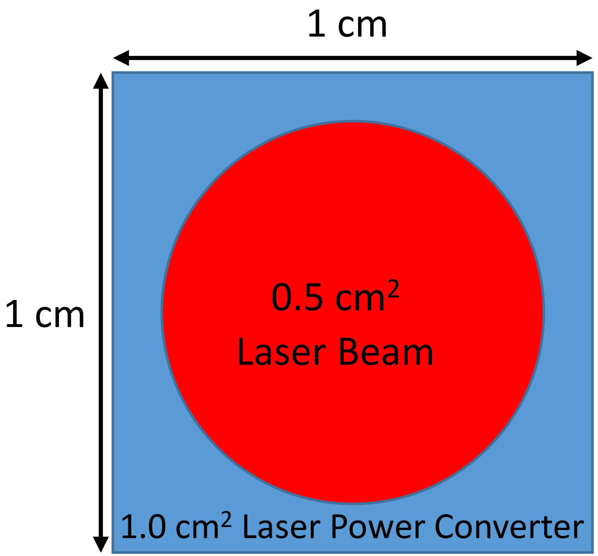
- Feasible in the near term
- Power beaming values assume a 1 kW laser at 1064 nm and a 1 m^2 laser power converter.
- Solar photovoltaics: 32% efficient solar cell. Power Beaming: 65% tuned laser power converter.

(1)Power beamed from orbit (e.g. Earth-Moon Lagrangian point)

(2)Power beamed from the surface of the moon

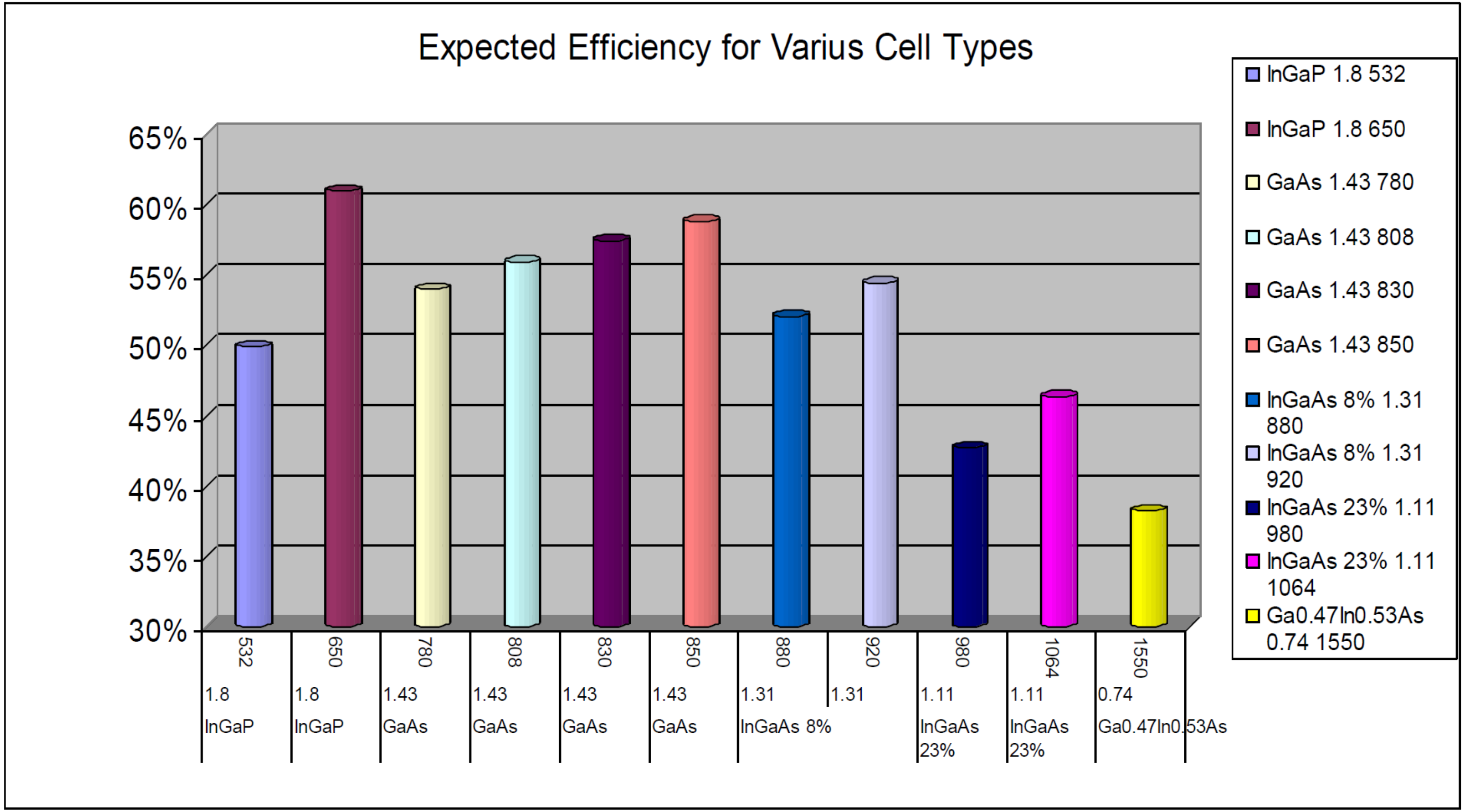
Power Beaming Facility





- Power beaming setup.
- Lab was approved for class 4 laser operation.
- Wavelength of the laser is 808 nm. Beam size is about 0.5 cm^2, half the area of the laser power converter.

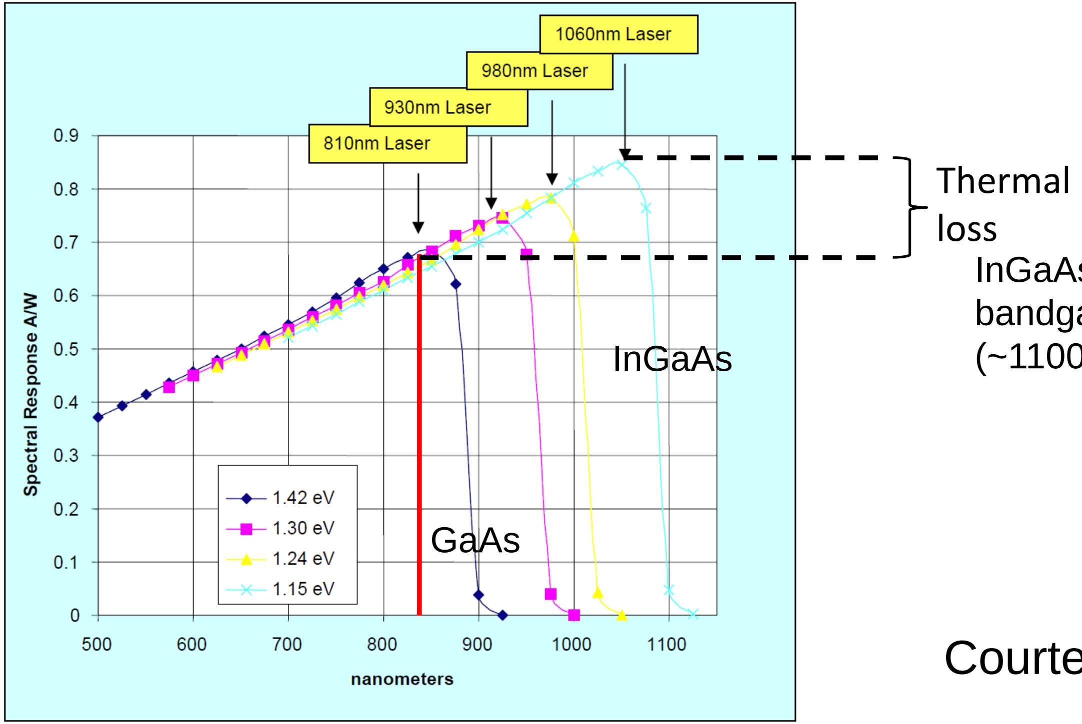
Laser Power Converters



Courtesy of Spectrolab

GaAs and InGaP bandgaps

Laser wavelength (808 nm) is well matched with room temperature GaAs bandgap (~900 nm) for optimal power conversion



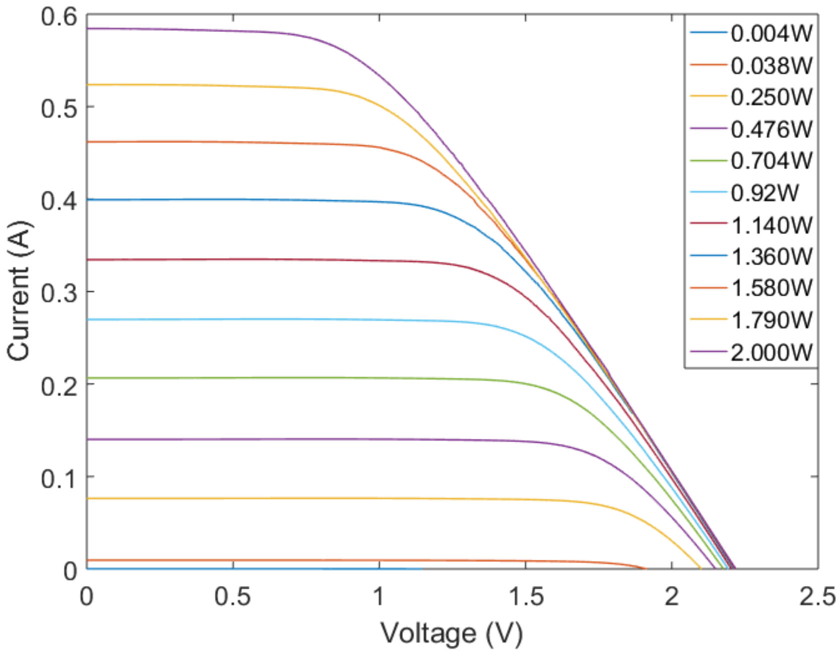
InGaAs bandgap (~1100 nm)

Courtesy of Spectrolab

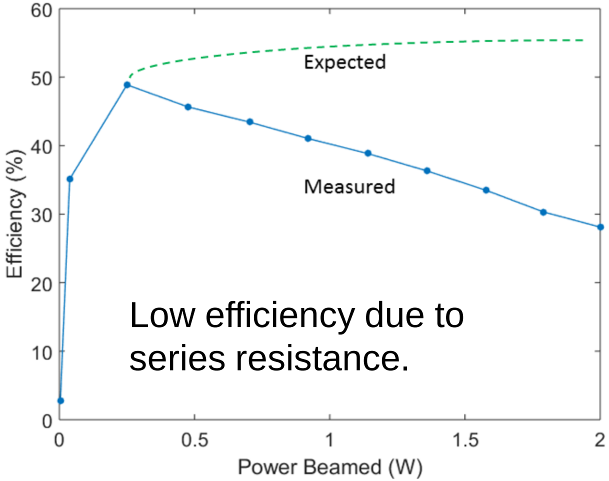
GaAs dual junction device result

I (A)	0.25	0.5	0.75	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75
P (W)	0.004	0.038	0.25	0.476	0.704	0.920	1.14	1.36	1.58	1.79	2.0
D (kW/m^2)	0.08	0.76	5	9.52	14.08	18.4	22.8	27.2	31.6	35.8	40

Optical power beamed out of the optical fiber as a function of the laser power supply current.

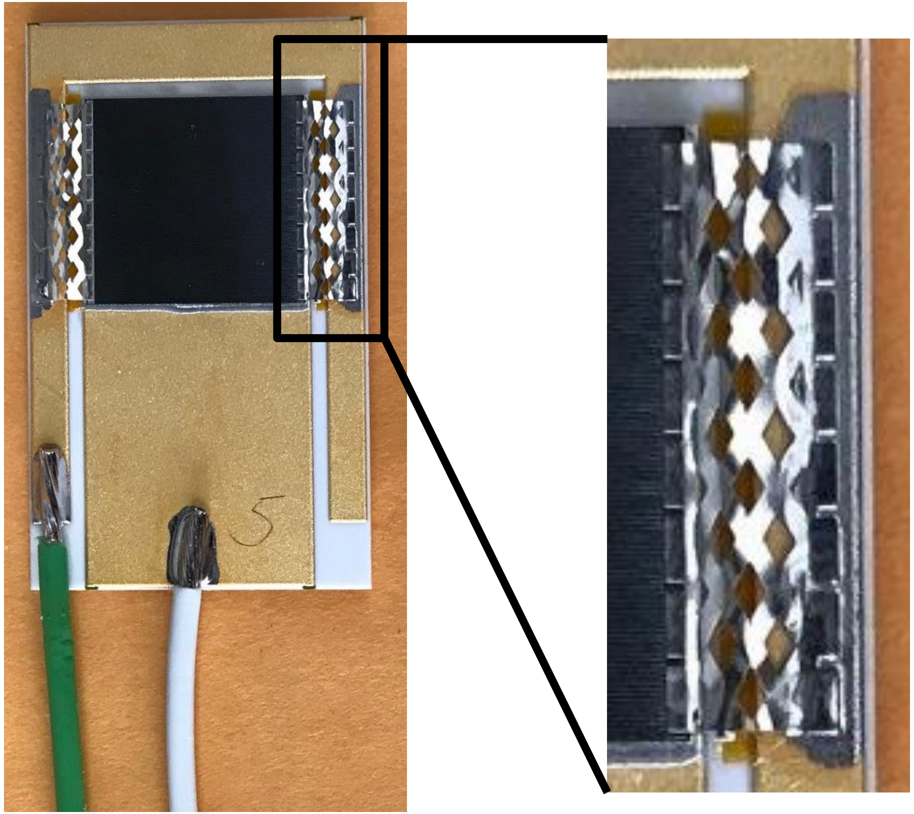


Current-Voltage measurement of the LPC while illuminated by an 808 nm wavelength laser beam.



Low efficiency due to series resistance.

InGaP laser power converter device



Large area integrated contacts

InGaAs Laser Power Converter Optimized for 1064 nm wavelength

Tested at 808 nm

InGaP device result tested with a 808 nm laser

I (A)	0.25	0.5	0.75	1.0	1.25	1.5	1.75	2.0	2.25	2.5	2.75
P (W)	0.004	0.038	0.25	0.476	0.704	0.920	1.14	1.36	1.58	1.79	2.0
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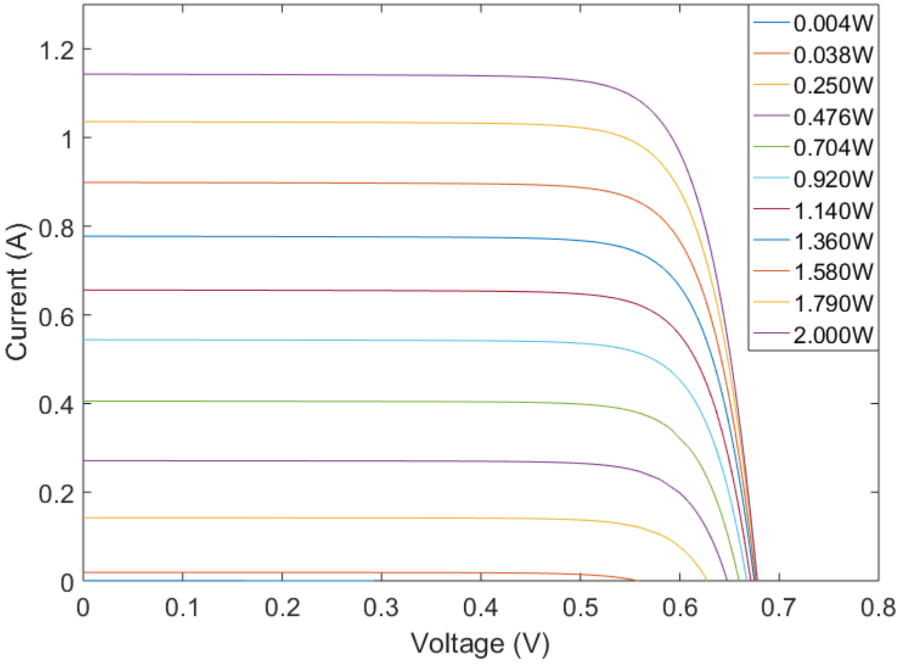
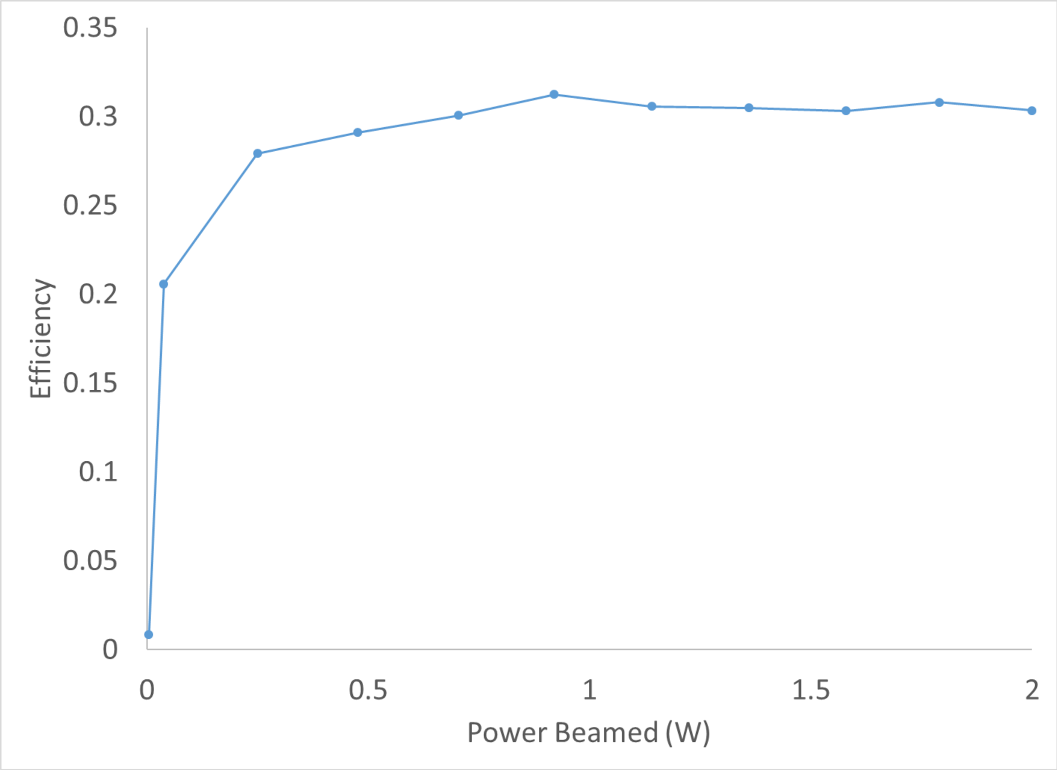


Current-Voltage measurement of the LPC while illuminated by an 808 nm wavelength laser beam.

InGaP device result

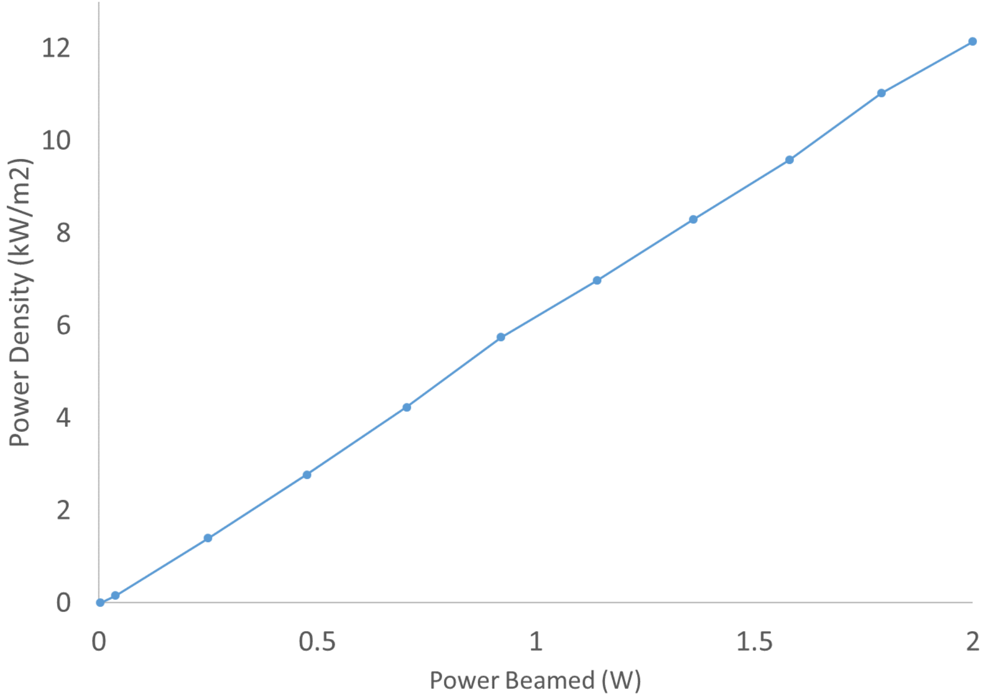
Efficiency stabilizes around 30% (808 nm laser)

With a 1064 nm laser, expected efficiency is 46%



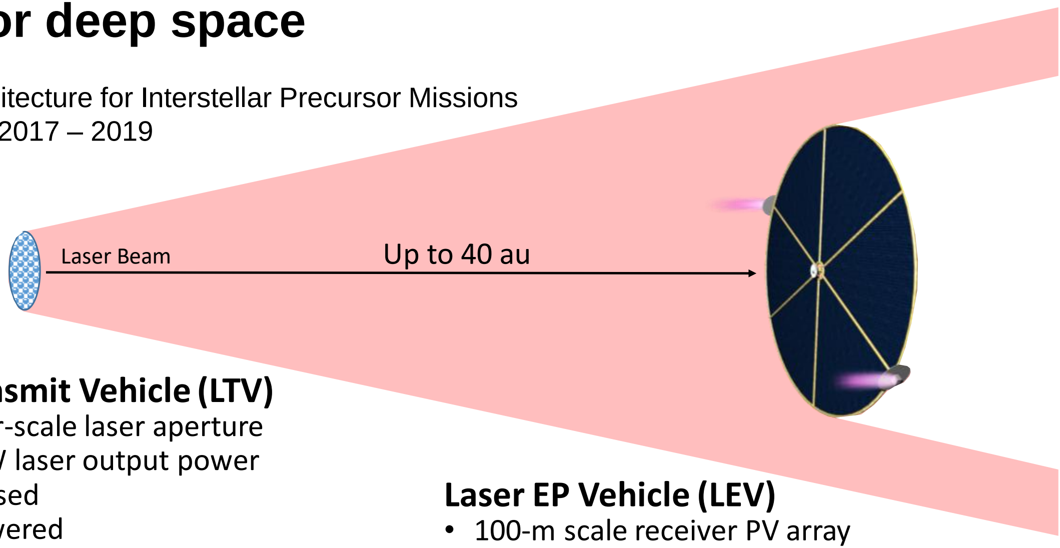
InGaP device result

Highest Measured power density is 12.14 kW/m^2
This corresponds to about 30 times a regular solar array at 1 AU.



Power beaming for deep space

A Breakthrough Propulsion Architecture for Interstellar Precursor Missions
NIAC study led by John Brophy 2017 – 2019



Laser Transmit Vehicle (LTV)
- Kilometer-scale laser aperture
- 100’s MW laser output power
- Space-based
- Solar Powered

Laser EP Vehicle (LEV)
- 100-m scale receiver PV array
  - Areal density ~100 g/m^2
  - Cell efficiency 50%
- 10 MW Direct-Drive, Lithium-Fueled EP System
  - Specific Impulse: 40,000 s

Depiction of a Directed-Energy Electric Propulsion (DEEP) propulsion architecture potentially capable to enabling missions with characteristic velocities of between 100 and 200 km/s. The architecture consists of a laser transmit vehicle (LTV) that is a high-power, large-aperture, space-based laser transmitter, and a laser electric propulsion vehicle (LEV) that collects a fraction of the laser power to operate an ultra-high specific impulse electric propulsion system.

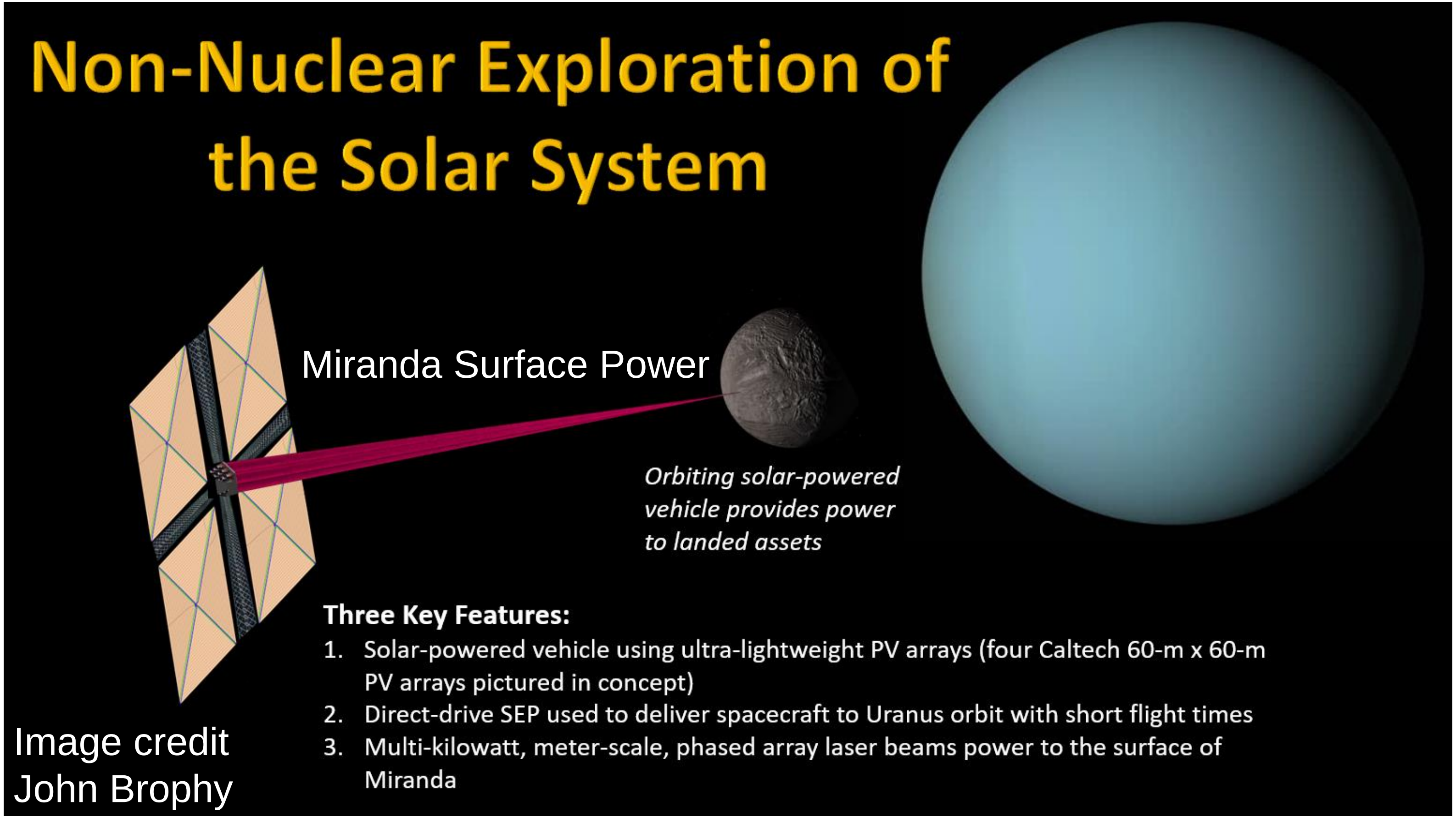
John R. Brophy, Jonathan Grandidier et al. Directed-Energy Propulsion Architecture for Deep-Space Missions with Characteristic Velocities of Order 100 km/s, The 36th International Electric Propulsion Conference, University of Vienna, Austria September 15-20, 2019.

Comparison Solar Photovoltaics / Power Beaming

Mission	Power Generated Solar photovoltaics (W m^{-2})	Generated Power Beaming (W)	Comparison vs Solar Photovoltaics
Jupiter (5.5 AU)	**14.4**	**3,678**	X 110
Saturn (10 AU)	**4.5**	**1,560**	X 160
Uranus (19.2 AU)	**1.3**	**403**	X 310
Neptune (30 AU)	**0.6**	**163**	X 272

- Far term concept
- Power beaming values assume a 100 MW with a 10 km aperture laser at 1064 nm and a 110 m diameter laser power converter.
- Solar photovoltaics: 32% efficient solar cell.
  Power Beaming: 65% tuned laser power converter.
- Power beamed from Space

JPL Blue Sky study April – September 2019



Conclusion

- Power beaming involves the wireless transfer of power, and could provide a revolutionary new way to power spacecraft and vehicles operating in difficult to access regions.

- Power beaming has the potential to represent an alternative solution to power spacecraft and landers where sunlight is unavailable.

- It could provide a source of power to robotic systems in permanently shadowed regions or power landers and rovers from orbiting spacecraft (e.g.,Moon, Mars, Europa, Enceladeus, Miranda).

- 12.14 kW/m2 power beaming measurements on a InGaAs LPC device was demonstrated.

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov